

PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

REC'D 07 SEP 1999

WIPO PCT

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Applicant's or agent's file reference 226315	FOR FURTHER ACTION See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)	
International application No. PCT/US98/05174	International filing date (day/month/year) 17 MARCH 1998	Priority date (day/month/year) 18 MARCH 1997
International Patent Classification (IPC) or national classification and IPC IPC(6): H01J 17/49 and US Cl.: 313/231.31, 582, 583,		
Applicant TRUSTEES OF THE STEVENS INSTITUTE OF TECHNOLOGY		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 4 sheets.

☒ This report is also accompanied by ANNEXES, i.e., sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority. (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

These annexes consist of a total of 3 sheets.

3. This report contains indications relating to the following items:

- I ☒ Basis of the report
- II ☐ Priority
- III ☐ Non-establishment of report with regard to novelty, inventive step or industrial applicability
- IV ☐ Lack of unity of invention
- V ☒ Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
- VI ☐ Certain documents cited
- VII ☐ Certain defects in the international application
- VIII ☐ Certain observations on the international application

Date of submission of the demand 17 SEPTEMBER 1998	Date of completion of this report 09 MAY 1999
Name and mailing address of the IPEA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer VIP PATEL Telephone No. (703) 305-4846

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No.

PCT/US98/05174

I. Basis of the report

1. This report has been drawn on the basis of *(Substitute sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to the report since they do not contain amendments):*

- ☐ the international application as originally filed.
- ☒ the description, pages (See Attached) , as originally filed.
pages _____ , filed with the demand.
pages _____ , filed with the letter of _____.
pages _____ , filed with the letter of _____.
- ☒ the claims, Nos. (See Attached) , as originally filed.
Nos. _____ , as amended under Article 19.
Nos. _____ , filed with the demand.
Nos. _____ , filed with the letter of _____.
Nos. _____ , filed with the letter of _____.
- ☒ the drawings, sheets/fig (See Attached) , as originally filed.
sheets/fig _____ , filed with the demand.
sheets/fig _____ , filed with the letter of _____.
sheets/fig _____ , filed with the letter of _____.

2. The amendments have resulted in the cancellation of:

- ☒ the description, pages None .
- ☒ the claims, Nos. None .
- ☒ the drawings, sheets/fig None .

3. ☐ This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed, as indicated in the ~~Supplemental Box~~ Additional observations below (Rule 70.2(c)).

4. Additional observations, if necessary:

None

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No.

PCT/US98/05174

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**1. STATEMENT**

Novelty (N)	Claims <u>1-23</u>	YES
	Claims <u>None</u>	NO
Inventive Step (IS)	Claims <u>1-23</u>	YES
	Claims <u>None</u>	NO
Industrial Applicability (IA)	Claims <u>1-23</u>	YES
	Claims <u>None</u>	NO

2. CITATIONS AND EXPLANATIONS

Claims 1-23 meet the criteria set out in PCT Article 33(2)-(4), because the prior art does not teach or fairly suggest a glow plasma discharge apparatus for generating and maintaining a glow plasma discharge comprising a pair of electrodes in facing relation having a space there between, a perforated dielectric having plurality of apertures of micron dimension placed over one of the electrodes and partially occupying the space.

----- NEW CITATIONS -----

None

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No.

PCT/US98/05174

Supplemental Box

(To be used when the space in any of the preceding boxes is not sufficient)

Sheet 10

Continuation of: Boxes I - VIII

I. BASIS OF REPORT:

THIS REPORT HAS BEEN DRAWN ON THE BASIS OF THE DESCRIPTION,
PAGES, 1-12, AS ORIGINALLY FILED.

PAGES, NONE, FILED WITH THE DEMAND.

AND ADDITIONAL AMENDMENTS:

NONE

THIS REPORT HAS BEEN DRAWN ON THE BASIS OF THE CLAIMS,

NUMBERS, NONE, AS ORIGINALLY FILED.

NUMBERS, NONE, AS AMENDED UNDER ARTICLE 19.

NUMBERS, NONE, FILED WITH THE DEMAND.

AND ADDITIONAL AMENDMENTS:

CLAIMS 1-23 FILED WITH THE LETTER OF 07 APRIL 1999.

THIS REPORT HAS BEEN DRAWN ON THE BASIS OF THE DRAWINGS,

SHEETS, 1-8, AS ORIGINALLY FILED.

SHEETS, NONE, FILED WITH THE DEMAND.

AND ADDITIONAL AMENDMENTS:

NONE



-13-

CLAIMSWhat is claimed is:

1. An apparatus for generating and maintaining a glow plasma discharge comprising:

a pair of electrodes positioned in facing relation;

a perforated dielectric placed over one of the electrodes; and

an electric field generated between the electrodes.

2. The apparatus of claim 1 wherein the perforated dielectric comprises a plurality of apertures, each aperture having a diameter ranging from 5 to 200 μ m.

3. The apparatus of claim 2 wherein the dielectric is between 100 μ m and 2mm in thickness.

4. The apparatus of claim 3 wherein the dielectric comprises silicon nitride.

5. The apparatus of claim 3 wherein the dielectric comprises silicon carbide.

6. The apparatus of claim 3 wherein a second dielectric is placed over the other of the electrodes.

7. The apparatus of claim 3 wherein the dielectric is a high temperature dielectric able to withstand high temperatures.

8. A cathode for generating and maintaining a glow plasma discharge comprising:

an electrode;

perforated dielectric means placed over the electrode; and

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means for retaining the perforated dielectric on the electrode.

9. The apparatus of claim 8 wherein the perforated dielectric means comprises a plurality of apertures, each aperture having a diameter ranging from 5 to 200 μ m.

10. The apparatus of claim 9 wherein the perforated dielectric means is between 100 μ m and 2mm in thickness.

11. The apparatus of claim 10 wherein the perforated dielectric means comprises silicon nitride.

12. The apparatus of claim 10 wherein the perforated dielectric means comprises silicon carbide.

13. The apparatus of claim 11 wherein a second perforated dielectric means is placed over the other of the electrodes.

14. The apparatus of claim 11 wherein the perforated dielectric means is a high temperature dielectric able to withstand high temperatures.

15. A method of stabilizing glow-to-arc transition for a discharge plasma comprising the steps of:

positioning opposing electrodes in a facing relation;

providing a perforated dielectric having a plurality of apertures therethrough; and

covering one of the electrodes with a perforated dielectric.

16. The method of claim 15 further comprising the step of covering the other of the electrodes with a perforated dielectric so that both electrodes are covered.

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17. The method of claim 15 wherein the step of covering one of the electrodes comprises placing a dielectric material thereon and retaining the dielectric material thereon.

18. The method of claim 17 wherein the step of retaining the dielectric material on one of the electrodes further includes the step of placing a retaining collar over the dielectric.

19. The method of claim 15 wherein the step of covering one of the electrodes comprises the step of depositing a dielectric on one of the electrodes.

20. The method of claim 19 wherein the step of depositing a dielectric on one of the electrodes comprises vapor deposition.

21. An apparatus for generating and maintaining a glow plasma discharge comprising:

a pair of electrodes positioned in facing relation, with a space therebetween;

a perforated dielectric positioned between the electrodes and partially occupying the space;
and

an electric field generated between the electrodes.

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference 226315	FOR FURTHER ACTION see Notification of Transmittal of International Search Report (Form PCT/ISA/220) as well as, where applicable, item 5 below.	
International application No. PCT/US98/05174	International filing date (day/month/year) 17 MARCH 1998	(Earliest) Priority Date (day/month/year) 18 MARCH 1997
Applicant TRUSTEES OF THE STEVENS INSTITUTE OF TECHNOLOGY		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 3 sheets.

☒ It is also accompanied by a copy of each prior art document cited in this report.

1. ☐ Certain claims were found unsearchable (See Box I).
2. ☐ Unity of invention is lacking (See Box II).
3. ☐ The international application contains disclosure of a nucleotide and/or amino acid sequence listing and the international search was carried out on the basis of the sequence listing
 - ☐ filed with the international application.
 - ☐ furnished by the applicant separately from the international application,
 - ☐ but not accompanied by a statement to the effect that it did not include matter going beyond the disclosure in the international application as filed.
 - ☐ transcribed by this Authority.
4. With regard to the title,
 - ☐ the text is approved as submitted by the applicant.
 - ☒ the text has been established by this Authority to read as follows:
Glow Plasma Discharge Device
5. With regard to the abstract,
 - ☐ the text is approved as submitted by the applicant.
 - ☒ the text has been established, according to Rule 38.2(b), by this Authority as it appears in Box III. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.
6. The figure of the drawings to be published with the abstract is:
Figure No. 1
 - ☒ as suggested by the applicant.
 - ☐ because the applicant failed to suggest a figure.
 - ☐ because this figure better characterizes the invention.

☐ None of the figures.



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Box III TEXT OF THE ABSTRACT (Continuation of item 5 of the first sheet)

NEW ABSTRACT

A glow plasma discharge device having an electrode (20, 40) covered with perforated dielectric (30) is disclosed.



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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/05174

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : H01J 17/49

US CL : 313/231.31, 582, 583,

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 313/231.31, 582, 583, 586, 619; 315/111.21, 111.71

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

None

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

None

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3,914,642 A (Coderre et al) 21 October 1975 (21-10-75), lines 30-45 of column 2.	1, 8, 21

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	*T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
A document defining the general state of the art which is not considered to be of particular relevance	*X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
E earlier document published on or after the international filing date	*Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	*A* document member of the same patent family
O document referring to an oral disclosure, use, exhibition or other means	
P document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

07 MAY 1998

Date of mailing of the international search report

15 JUN 1998

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WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

(51) International Patent Classification ⁶ : H01J 17/49		A1	(11) International Publication Number: WO 98/42002
			(43) International Publication Date: 24 September 1998 (24.09.98)
(21) International Application Number: PCT/US98/05174 (22) International Filing Date: 17 March 1998 (17.03.98) (30) Priority Data: 08/820,013 18 March 1997 (18.03.97) US (63) Related by Continuation (CON) or Continuation-in-Part (CIP) to Earlier Application US 08/820,013 (CIP) Filed on 18 March 1997 (18.03.97) (71) Applicant (for all designated States except US): TRUSTEES OF THE STEVENS INSTITUTE OF TECHNOLOGY [US/US]; Castle Point on Hudson, Hoboken, NJ 07030 (US). (72) Inventors; and (75) Inventors/Applicants (for US only): KUNHARDT, Erich, E. [US/US]; 807 Castle Point Terrace, Hoboken, NJ 07030 (US). BECKER, Kurt, H. [DE/US]; Apartment 10B, 25 East 9th Street, New York, NY 10003 (US). (74) Agent: FRISCIA, Michael, R.; Friscia & Nussbaum, One University Plaza, Hackensack, NJ 07601 (US).		(81) Designated States: AU, CA, JP, KR, US, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published <i>With international search report.</i> <i>With amended claims.</i>	
(54) Title: GLOW PLASMA DISCHARGE DEVICE (57) Abstract <p>A glow plasma discharge device having an electrode (20, 40) covered with perforated dielectric (30) is disclosed.</p>			

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
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EE	Estonia			SG	Singapore		

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GLOW PLASMA DISCHARGE DEVICE

SPECIFICATIONBACKGROUND OF THE INVENTIONFIELD OF THE INVENTION

10 This invention generally relates to a method and apparatus for the suppression of the glow-to-arc transition in DC and RF glow discharges, and more specifically to a cathode configuration having a perforated dielectric covering for stabilizing glow plasma discharges.

RELATED ART

15 A "plasma" is a partially ionized gas composed of ions, electrons, and neutral species. This state of matter is produced by high temperatures or strong electric fields created by constant or pulsed DC current, AC current or time varying (e.g., R.F. or microwave) electromagnetic fields. Discharge plasmas are produced when free electrons are energized by electric fields in a background of neutral atoms / molecules. These electrons cause electron - atom / molecule
20 collisions which transfer energy to the atoms / molecules and form a variety of species which may include photons, metastables, atomic excited states, free radicals, molecular fragments, monomers, electrons, and ions. The neutral gas becomes partially (or fully) ionized and is able to conduct currents. The plasma species are chemically active and/or can physically modify the surface of materials and may therefore serve as the basis of new chemical compounds and may be used to
25 modify existing compounds. Discharge plasmas can also produce useful amounts of optical radiation and can therefore be used in lighting. There are additionally many other uses for such plasmas. Glow discharges and arc discharges produce a class of plasmas known as current-maintained plasmas, since they are maintained by the passage of current therethrough. Such plasmas conduct only because current is passed therethrough and the conductivity falls off quickly
30 if the source of energy to the charge carriers is removed.

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Transition points exist at which the various attributes of the discharge and discharge plasma change from the characteristics of a glow discharge to the characteristics of an arc discharge. The characteristics that distinguish arc from glow are a high gas temperature and a low cathode fall potential, though it is also possible to have a high gas temperature associated with a high cathode fall and vice versa.

The transition from glow to arc passes through a series of stable or quasi-stable states. However, the final step from abnormal glow to arc is very often an unstable change, since a very large potential drop in the series resistance would be required to make it stable. If there is no series resistance, the transition may take place very rapidly, without equilibrium being achieved in any intermediate stage. This transition becomes more rapid as the pressure of the background neutral gas increases towards atmospheric pressure.

In the past, there have been efforts to stabilize glow plasma discharges in various ways such as the use of source frequencies over 1 kHz, insertion of a dielectric plate (or plates) between two metal electrodes and by using helium dilution gas. Additionally, other attempts to stabilize the glow plasma discharge include placement of an insulated plate on the lower electrode, use of a brush-style upper electrode, and the use of a metal upper plate in combination with an insulating plate on the bottom thereof. However, there are certain drawbacks with these requirements in that, e.g. helium is expensive and there are physical limitations based on the structure of the electrodes and the insulated plates.

Past work in this area include a series of articles by Okazaki, Satiko, et al., starting back in 1989 with the article by Kanazaw, S., et al., entitled, "Glow Plasma Treatment at Atmospheric Pressure for Surface Modification and Film Deposition," Nuclear Instruments and Methods in Physics Research (1989) Elsevier Science Publishers, B.V. (North-Holland Physics Publishing Division), which disclosed a plasma treatment at atmospheric pressure to stabilize glow plasma by treatment in a gas which includes carbon-tetrafluoride (CF_4), using helium as the dilute gas and using an insulating plate on a lower electrode, and using a brush style electrode for the upper electrode to create a stable discharge at 3,000 Hz.

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5 Yokoyama, T., et al., "The improvement of the atmospheric-pressure glow plasma method and the deposition of organic films," Journal of Physics (1990) IOP Publishing, Ltd., discloses an improved atmospheric pressure glow discharge plasma method for treating metallic substrates wherein the middle plate upper electrode is improved by use of an insulating plate set on its bottom.

10 Yokoyama, T. et al., "The mechanism of the stabilization of glow plasma at atmospheric pressure," Journal of Physics (1990) IOP Publishing, Ltd., discloses stabilization of a glow discharge of atmospheric pressure by controlling three conditions, namely, the use of a high frequency source, the use of helium gas for dilution, and the insertion of a dielectric plate between electrodes.

15 Okazaki, Satiko, et al., "Appearance of stable glow discharge in air, argon, oxygen, and nitrogen at atmospheric pressure using a 50 Hz source," Journal of Physics, (1993) IOP Publishing, Ltd., discloses a method and apparatus for stabilizing glow discharge by making the discharge occur in the early stages of the Kekez curve, and at a lower discharge breakdown voltage, by use of a metal wire mesh electrode.

20 Kogoma, Masuhiro, et al., "Raising of ozone formation efficiency in a homogeneous glow discharge plasma at atmospheric pressure," Journal of Physics (1994) IOP Publishing, Ltd., discloses an ozone formation apparatus for increasing the efficiencies of ozone formation by use of a homogenous glow discharge at atmospheric pressure to create ozone efficiencies increased to about 10% in air to a maximum of 15% in oxygen over conventional filamentary current discharges in gas. The increase is attributed to better collision efficiency among electrons and molecules and to a lower increase in temperature than in discharge filaments of a silent electric discharge.

30 Other work in this area includes U.S. Patent No. 4, 498,551 to Hoag, entitled, "Discharge Electrode for a Gas Discharge Device," which uses pin-shaped electrodes which are effectively cooled in the glass flow and which promote a stable glow-discharge.

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U.S. Patent No. 5,387,842 dated February 7, 1995 to Roth, et al., entitled, "Steady-State, Glow Discharge Plasma," and U.S. Patent No. 5,414,324 dated May 9, 1995 to Roth, et al., entitled "One Atmosphere, Uniform Glow Discharge Plasma," both disclose a steady state glow discharge plasma generated between a pair of insulated metal plate electrodes spaced up to five centimeters apart and energized with a RMS potential of 1 to 5 KV at 1 to 100 Khz. The space between the electrodes is occupied by a noble gas such as helium, neon, argon, etc., and it may also include air. The radio frequency amplifier means for generating and maintaining a glow discharge plasma includes an impedance matching network. The arc of electric field is high enough to trap the positive ions of the plasma between the electrodes, but not so high that the electrons of the plasma are also trapped during a half cycle of the RF voltage.

None of these previous efforts disclose all of the benefits of the present invention, nor does the prior art teach or suggest all of the elements of the present invention.

OBJECTS AND SUMMARY OF THE INVENTION

It is a primary object of the present invention to provide a method and apparatus for stabilizing glow discharge plasmas.

It is another object of the present invention to provide a method and apparatus for suppressing the glow-to-arc transition in glow discharges.

It is an additional object of the present invention to provide a method and apparatus to stabilize glow discharge plasmas in a constant electric field.

It is even an additional object of the present invention to provide a method and apparatus to stabilize glow discharge plasmas in time varying electric fields.

It is another object of the invention to provide a cathode configuration for stabilizing the cathode fall in a glow discharge.

It is an additional object of the present invention to provide a method and apparatus for suppressing the glow-to-arc transition for a wide range of operating conditions and a wide range of operating pressures.

It is another object of the present invention to provide a metal cathode covered with a perforated dielectric for suppressing the glow-to-arc transition and stabilizing glow discharge.

It is also an object of the present invention to provide a method and apparatus for suppressing the glow-to-arc transition for a wide range of electric field strengths.

It is an additional object of the present invention to tailor the characteristics of fuel combustion by field augmentation with suppression of the glow-to-arc transition.

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It is an additional object of the present invention to tailor the characteristics of plasma assisted materials processing by suppressing the glow-to-arc transition in material processing.

5 It is another object of the present invention to suppress the glow-to-arc transition and to allow for large volume plasma work at atmospheric pressure.

It is an additional object of the present invention to reduce the complexity and costs of plasma processing of materials.

10 It is even a further object of the present invention to improve pollution control through the use of plasmas at high pressures by suppressing the glow-to-arc transition.

15 These and other objects are achieved by the method and apparatus of the present invention for stabilizing glow plasma discharges by suppressing the transition from glow-to-arc. A dielectric plate having an upper surface and a lower surface and a plurality of holes extending therethrough is positioned over the cathode and held in place thereon by a collar. Each of the holes acts as a separate active current limiting micro-channel that prevents the overall current density from increasing above the threshold for the glow-to-arc transition.

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BRIEF DESCRIPTION OF THE DRAWINGS

Other important objects and features of the invention will be apparent from the following Detailed Description of the Invention when read in context with the accompanying drawings in which:

FIG. 1 is an exploded perspective view of the perforated dielectric covering a cathode of a DC embodiment of the present invention.

FIG. 2 is a schematic view of a circuit configuration for use with the present invention.

FIG. 3 is a graph of voltage v. current for applied voltage, glow voltage, and arc voltage in Argon at 40 Torr.

FIG. 4 is a graph of voltage v. current for applied voltage, glow voltage, and arc voltage in Argon at 20 Torr.

FIGS. 5a and 5b are graphs of applied voltage, glow voltage and arc voltage with and without the perforated dielectric of the present invention.

FIG. 6a is a photograph showing an arc discharge and **FIG 6b** is a photograph showing a glow discharge.

FIG. 7 is a side plan view of another embodiment of the present invention for an RF field wherein perforated dielectrics are positioned over both electrodes.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is directed to a method and apparatus for stabilizing plasma glow discharges by suppressing the glow-to-arc transition in DC, RF electric field, pulsed DC, AC current or any other glow discharges which evolves from the cathode fall region. Referring to **FIG. 1**, it can be seen that a new cathode configuration has been developed to stabilize the cathode fall and suppress the glow-to-arc transition for a wide range of operating conditions. Accordingly, a stable glow discharge can be maintained with the cathode configuration of the present invention for a very wide range of operating pressures (up to atmospheric pressures) and in a wide range of electric field strengths.

Referring to **FIG. 1**, which shows a DC embodiment, the cathode of the present invention, generally indicated at **10**, comprises a metal cathode **20** (aluminum, stainless steel, etc.), covered with a perforated dielectric **30** positioned to face an upper electrode **40**. The perforated dielectric **30** may be retained on the cathode **20** by a collar **35** that fits over cathode **20** and has an aperture **36** therethrough, or may be formed as part of a cap or cover for the cathode **20**, or may be positioned thereon and held in place thereon in any other manner known in the art.

Importantly, the perforated dielectric can be formed of any desired dielectric type substance such as quartz, silicon nitride, silicon carbide, etc., even glass. The dielectric is preferably formed of a material that can withstand high temperatures. Essentially, a perforated dielectric comprises a sieve of holes of micron dimensions. The center to center distance of the holes is of the same level of dimension. Hole dimensions are critical for particular applications. In trials discussed hereinafter, a dielectric having 10 micron holes with a center to center distance between the holes of 12 microns was used. Hole dimensions can vary from 5 to 200 μm for the hole diameter and from between 100 μm to 2 mm for the hole length (thickness of the dielectric). Importantly, the ratio of the hole diameter to the dielectric thickness is an important factor and something that can be controlled depending upon the application. One example of such a ratio could be 10 to 1, the hole diameter being one-tenth of the thickness of the dielectric.

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The perforated dielectric can be made by laser ablation. Blanks for dielectric plates made by Norton International can be used, and function in a desirable matter (a dielectric having a hole diameter of 10 μm , and a hole length of 0.6 mm). The hole diameter, hole lengths, hole density, and material can be varied to optimize the invention for a particular application. Any silicon carbide wafer can be perforated by laser ablation to form a perforated dielectric for use in connection with the present invention.

Referring to FIG. 2, shows a circuit that has been used to conduct trials of the present invention that will hereinafter be discussed, which can be used with the cathode configuration of the present invention to effect a stable DC glow plasma discharge. The circuit is governed by equation (1):

$$V_s = I_1 (R_1 + R_2) = \frac{1}{R_1} (R_1 + R_2)V \quad \text{Equation (1)}$$

where $I_2 = 4I$

$$R_E \approx \frac{R_3}{4} \quad (\text{for } R_1 \ll R_3)$$

$$V_g = V_s - I_g R_3$$

$$V_d = V_s - I_d R_3$$

In this way, by measuring voltage V across resistor R , and current i through resistor R_1 , we can calculate the voltage and the current across the cathode 10.

The present invention allows DC glow discharges, which have a well known instability that limits the operating range, to operate at much higher pressure up to atmospheric pressures. Accordingly, this stabilization allows for applications in many aspects of material processing, pollution remediation, novel lighting devices, and discharge-enhanced combustion.

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The perforated dielectric covering the metal cathode stabilizes the cathode fall region of the DC discharge by breaking the discharge up into a large number of separate micro-channels. Each of the holes comprising the perforated dielectric acts as a separate, active current-limiting micro-channel. Particle losses due to wall effects and the finite volume of each channel place an upper limit on the electrical conductivity of each channel, and therefore place an upper limit on the current density that it can carry. This prevents the current density from increasing above the threshold for the glow-to-arc transition.

Additionally, it should be noted that a dielectric material could be directly deposited in a proper geometry directly onto a cathode by a vapor deposition or other process to apply the dielectric directly to the cathode. In this way, the cathode itself becomes an active current-limiting device.

A prototype DC glow discharge apparatus was set up using a parallel plate electrode arrangement in an Argon atmosphere of between 10-100 Torr, to illustrate the present invention.

At these pressures, the phases of the glow-to-arc transition can be readily shown because the transition is sufficiently slow. The transition at atmospheric pressures occurs very rapidly and is difficult to observe. However, it should be pointed out that the present invention is designed to be used at pressures up to atmospheric pressures. Current voltage characteristics were recorded for a variety of operating conditions using a standard metal (Al) cathode. The measured curves show the well-known first transition corresponding to the breakdown of gas in the formation of a stable glow discharge, followed by a prominent second transition characteristic of the transition from the glow regime to an arc which creates a filamentary (high current density) channel. Subsequently, the conventional cathode was replaced by the new cathode design and the same current-voltage curves were recorded. All curves showed only the first transition to the stable high-current glow. No indications of the previously observed glow-to-arc transition were found under any operating conditions. The spatial distribution of the discharge is also diffuse.

Referring now to **FIG. 3**, a graph of voltage vs. current for applied voltage (VG), glow voltage (Vg) and arc voltage (Vd) is shown for Argon at 40 Torr. **FIG. 4** shows a graph of voltage

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vs. current for applied voltage (VG), glow voltage (Vg), and arc voltage (Vd) in Argon at 20 Torr.

FIGS. 5a and 5b are graphs of the applied voltage and glow-to-arc voltage with and without the perforated dielectric of the present invention. These figures show the stabilization of the glow plasma discharge. In a first Stage A, there is no current. In the second Stage B, voltage is applied, but current stays at zero. In a third Stage C, a glow discharge is achieved. As seen in **FIG. 5a**, the glow quickly goes to arc D, while in **FIG. 5b**, the perforated dielectric suppresses the glow-to-arc transition and stabilizes the glow discharge such that there is no arc.

FIG. 6a is a photograph showing an arc discharge which creates a filamentary (high current density) channel. **FIG. 6b** is a photograph showing a glow discharge characterized by a uniform glow discharge.

FIG. 7 is a side plan view of an RF discharge embodiment of the present invention wherein the perforated dielectric is positioned over both electrodes. As can be seen electrodes **120** and **140** are both covered by a perforated dielectric **130**. Because the current reverses itself in a RF electric field, the dielectric **130** must be positioned over both electrodes **120** and **140**, as both electrodes alternately serve as cathodes. By this configuration, the glow discharge can be sustained under broader operating conditions. Such a configuration results in a frequency independent and size independent device.

By applying the method and apparatus of the present invention to large volume plasmas at atmospheric pressures, it is possible to increase the energy released during combustion of fuels to levels several times higher than the Heating Value of the fuel. Efforts in this area in the past have failed because the distribution of energy is required over a substantial volume and cannot be concentrated in a small area. Because of the glow-to-arc transition, there has been tendency to produce arcs of a very high energy level with the rest of the volume remaining at a normal combustion level. By suppressing the glow-to-arc transition and stabilizing the plasma glow, the method and apparatus of the present invention overcomes the limitations of the prior attempts and results in an enhancement of the combustion process resulting in much higher energy densities than

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could be previously achieved.

Additional applications of the present invention may occur in the field of air pollution remediation where stabilization of the glow-to-arc transition may result in real time destruction of constituents of air emissions from manufacturing operations in remediation of soil and ground water pollution, in large volumes at high pressures. By suppressing the glow-to-arc transition and stabilizing the glow discharge, the present invention creates large volume plasmas to destroy the polluting vapors at higher efficiencies with reduced cost. There could be additional applications relating to the destruction of combustion by-products such as NO_x and SO_x which have heretofore been destroyed by pulsed corona and barrier discharges.

The present invention is additionally applicable to the cleaning of lithography sheet surfaces in atmospheric pressures. Additionally, there may be possible utility for large area surface cleaning at atmospheric pressure for curing polymer films. By being able to operate at atmospheric pressure, a great advantage is achieved over the high processing cost required in a vacuum process. Additionally, the present invention can be used for pretreatment of semi-conductors, glasses, and polymers which are to be used for direct metal ion beam processing.

Additionally, an atmospheric pressure glow discharge plasma can be used to sterilize biologically contaminated surfaces. Current techniques in this area utilize high temperatures, strong chemicals, and/or ultraviolet radiation to sterilize contaminated items. However, there are problems with these approaches in that the processes are time intensive and potentially hazardous and result in the formation of potentially hazardous by-products. It has been demonstrated that materials exposed to a one-atmosphere pressure glow discharge plasma can be sterilized of biological contaminants in under one minute.

Having thus described the invention in detail, it is to be understood that the foregoing description is not intended to limit the spirit and scope thereof. What is desired to be protected by the Letters Patent is set forth in the appended claims.

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CLAIMSWhat is claimed is:

1. An apparatus for generating and maintaining a glow plasma discharge comprising:
5
a pair of electrodes positioned in facing relation;
a perforated dielectric placed over one of the electrodes; and
10 an electric field generated between the electrodes.
2. The apparatus of claim 1 wherein the perforated dielectric comprises a plurality of apertures, each aperture having a diameter ranging from 5 to 200 μ m.
- 15 3. The apparatus of claim 2 wherein the dielectric is between 100 μ m and 2mm in thickness.
4. The apparatus of claim 3 wherein the dielectric comprises silicon nitride.
5. The apparatus of claim 3 wherein the dielectric comprises silicon carbide.
- 20 6. The apparatus of claim 3 wherein a second dielectric is placed over the other of the electrodes.
7. The apparatus of claim 3 wherein the dielectric is a high temperature dielectric able to withstand high temperatures.
- 25 8. A cathode for generating and maintaining a glow plasma discharge comprising:
an electrode;
30 perforated dielectric means placed over the electrode; and

means for retaining the perforated dielectric on the electrode.

9. The apparatus of claim 8 wherein the perforated dielectric means comprises a plurality of
5 apertures, each aperture having a diameter ranging from 5 to 200 μ m.

10. The apparatus of claim 9 wherein the perforated dielectric means is between 100 μ m and 2mm
in thickness.

10 11. The apparatus of claim 10 wherein the perforated dielectric means comprises silicon nitride.

12. The apparatus of claim 10 wherein the perforated dielectric means comprises silicon carbide.

13. The apparatus of claim 11 wherein a second perforated dielectric means is placed over the
15 other of the electrodes.

14. The apparatus of claim 11 wherein the perforated dielectric means is a high temperature
dielectric able to withstand high temperatures.

20 15. A method of stabilizing glow-to-arc transition for a discharge plasma comprising the steps of:

positioning opposing electrodes in a facing relation;

25 providing a perforated dielectric having a plurality of apertures therethrough; and

covering one of the electrodes with a perforated dielectric.

16. The method of claim 15 further comprising the step of covering the other of the electrodes
30 with a perforated dielectric so that both electrodes are covered.

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17. The method of claim 15 wherein the step of covering one of the electrodes comprises placing a dielectric material thereon and retaining the dielectric material thereon.

18. The method of claim 17 wherein the step of retaining the dielectric material on one of the electrodes further includes the step of placing a retaining collar over the dielectric.

19. The method of claim 15 wherein the step of covering one of the electrodes comprises the step of depositing a dielectric on one of the electrodes.

20. The method of claim 19 wherein the step of depositing a dielectric on one of the electrodes comprises vapor deposition.

21. An apparatus for generating and maintaining a glow plasma discharge comprising:

a pair of electrodes positioned in facing relation, with a space therebetween;

a perforated dielectric positioned between the electrodes and partially occupying the space;
and

an electric field generated between the electrodes.

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FIG. 1

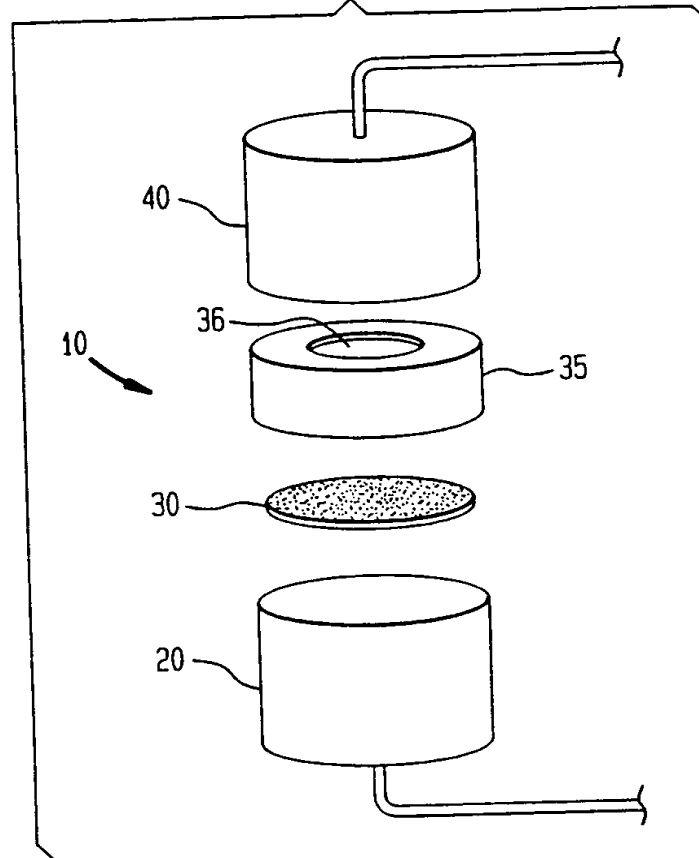
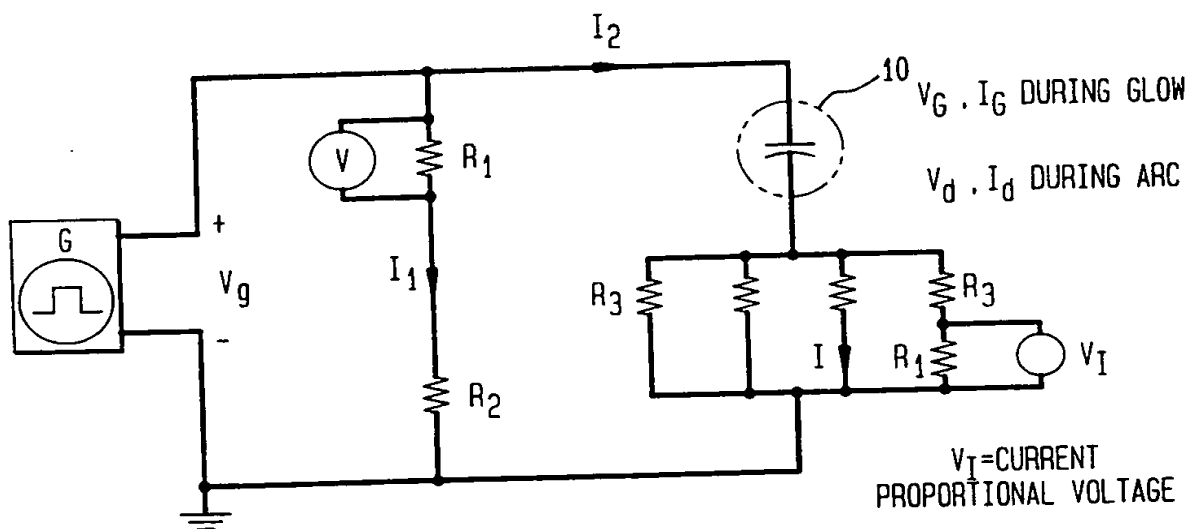


FIG. 2



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FIG. 3

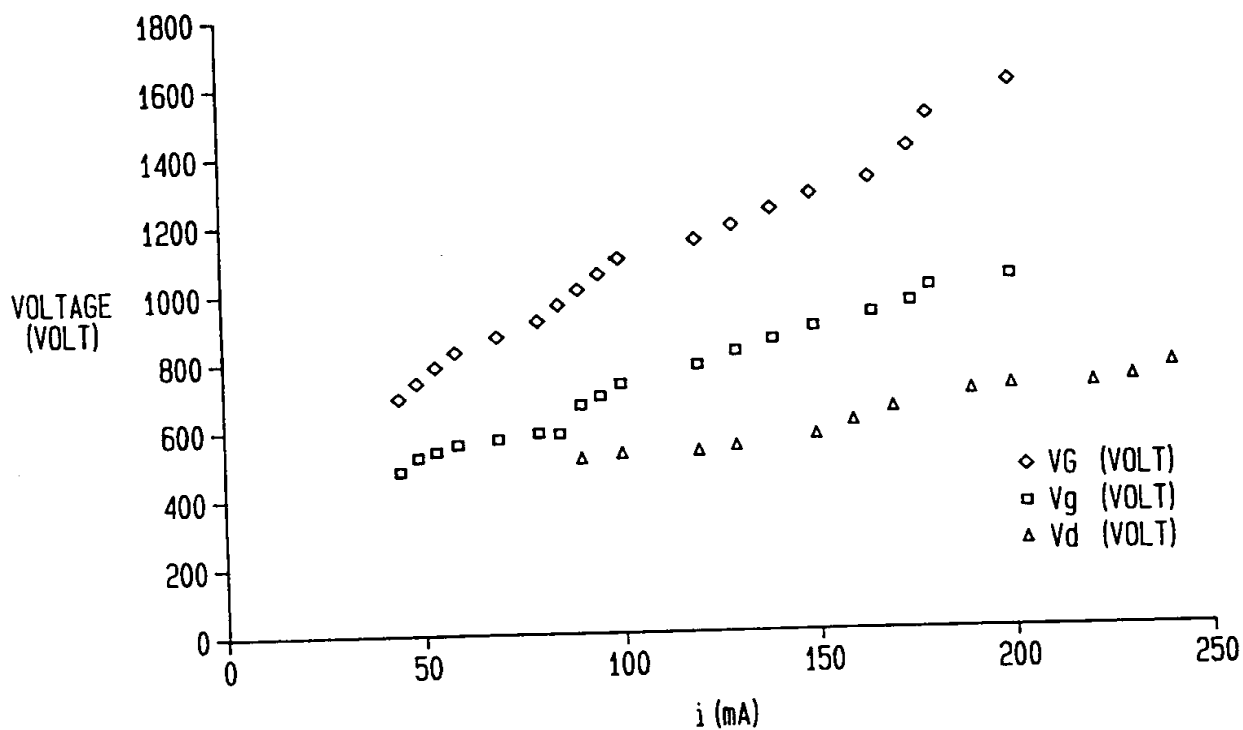
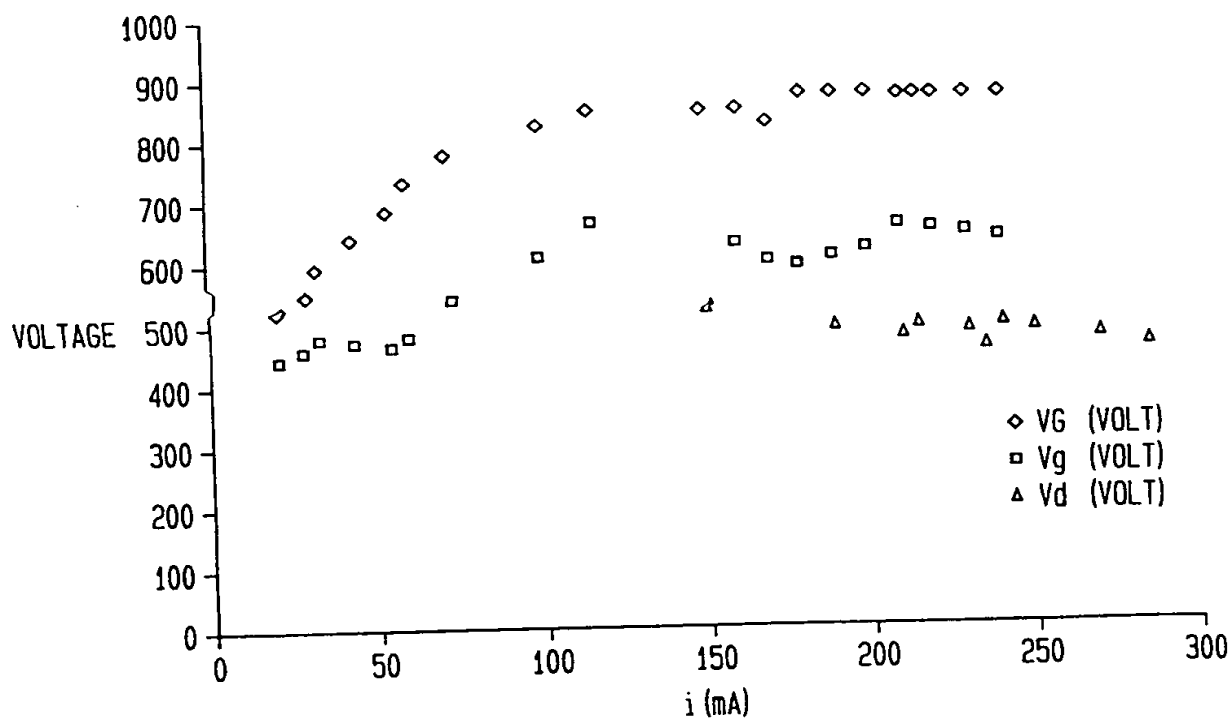


FIG. 4



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FIG. 5A

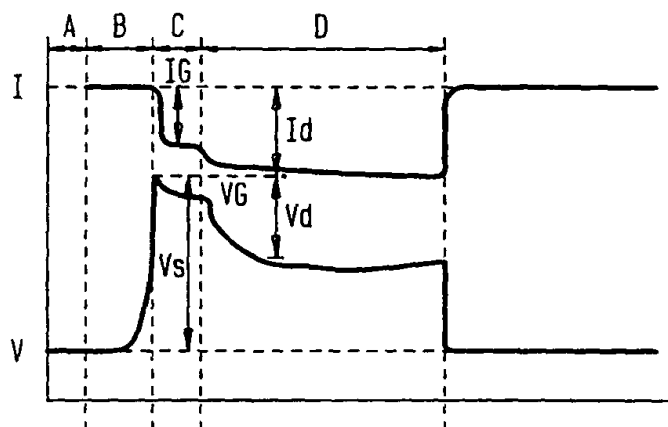


FIG. 5B

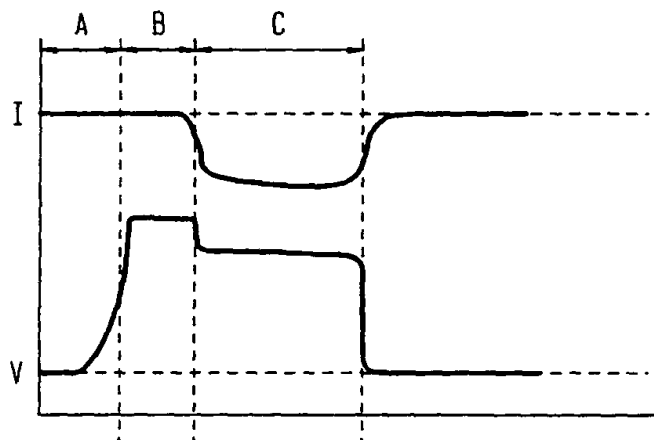
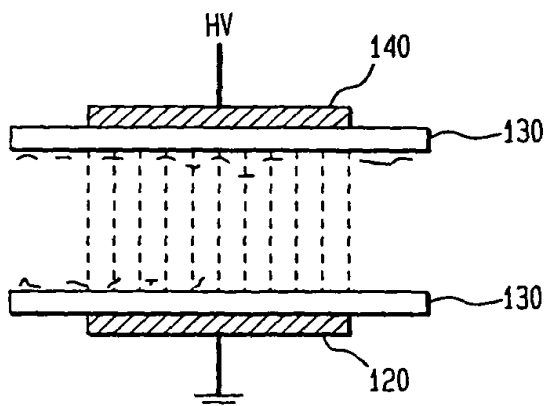


FIG. 7

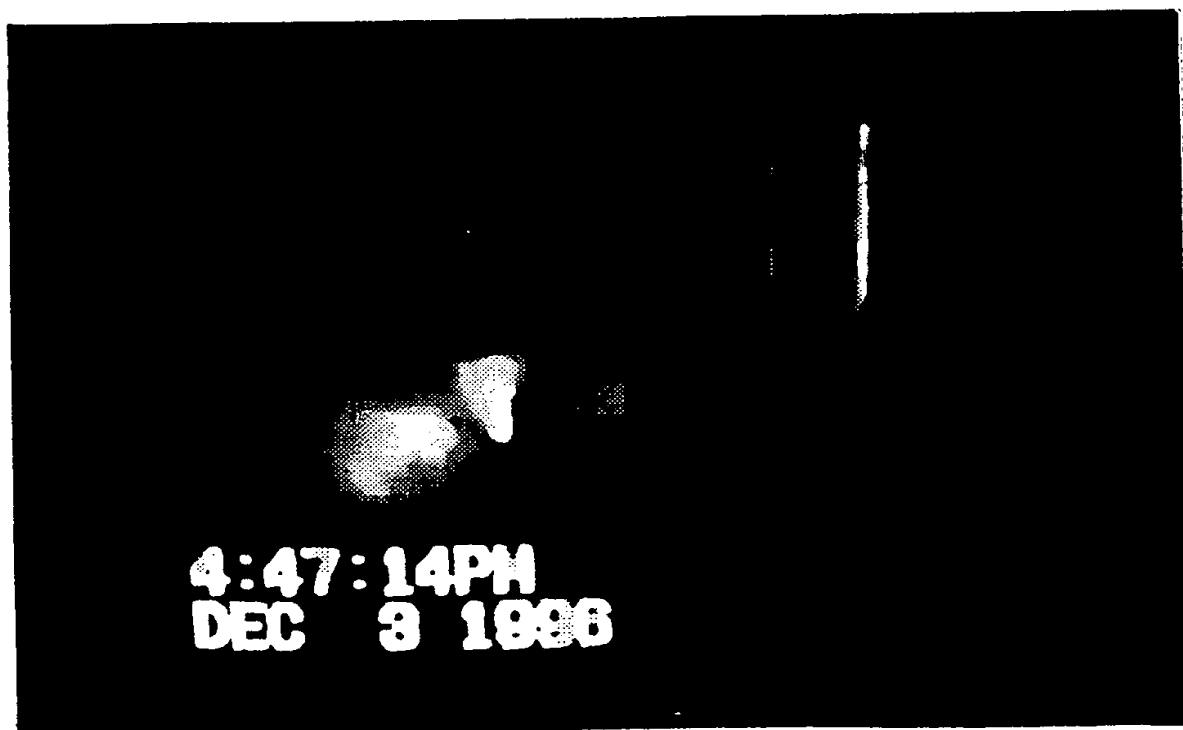


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FIG. 6A



FIG. 6B



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/05174

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H01J 17/49

US CL :313/231.31, 582, 583,

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 313/231.31, 582, 583, 586, 619; 315/111.21, 111.71

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NoneElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)
None

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3,914,642 A (Coderre et al) 21 October 1975 (21-10-75), lines 30-45 of column 2.	1, 8, 21

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(21) International Application Number: PCT/US98/05174 (22) International Filing Date: 17 March 1998 (17.03.98) (30) Priority Data: 08/820,013 18 March 1997 (18.03.97) US (63) Related by Continuation (CON) or Continuation-in-Part (CIP) to Earlier Application US 08/820,013 (CIP) Filed on 18 March 1997 (18.03.97) (71) Applicant (for all designated States except US): TRUSTEES OF THE STEVENS INSTITUTE OF TECHNOLOGY [US/US]; Castle Point on Hudson, Hoboken, NJ 07030 (US). (72) Inventors; and (75) Inventors/Applicants (for US only): KUNHARDT, Erich, E. [US/US]; 807 Castle Point Terrace, Hoboken, NJ 07030 (US). BECKER, Kurt, H. [DE/US]; Apartment 10B, 25 East 9th Street, New York, NY 10003 (US). (74) Agent: FRISCIA, Michael, R.; Friscia & Nussbaum, One University Plaza, Hackensack, NJ 07601 (US).		(81) Designated States: AU, CA, JP, KR, US, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published With international search report. With amended claims.
(54) Title: GLOW PLASMA DISCHARGE DEVICE (57) Abstract <p>A glow plasma discharge device having an electrode (20, 40) covered with perforated dielectric (30) is disclosed.</p> <div data-bbox="860 1155 1429 1974"><p>The diagram illustrates a glow plasma discharge device. It consists of a cylindrical outer electrode (20) and a central electrode (40). The outer electrode is covered with a perforated dielectric layer (30). A cross-section of the dielectric layer (30) is shown separately, revealing its perforated structure. The dielectric layer is labeled 30, the outer electrode is 20, and the central electrode is 40. A cross-section of the dielectric layer is also labeled 36 and 35.</p></div>		



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GLOW PLASMA DISCHARGE DEVICE

TITLE: METHOD AND APPARATUS FOR SUPPRESSION OF
THE GLOW-TO-ARC TRANSITION IN GLOW DISCHARGES

SPECIFICATIONBACKGROUND OF THE INVENTIONFIELD OF THE INVENTION

This invention generally relates to a method and apparatus for the suppression of the glow-to-arc transition in DC and RF glow discharges, and more specifically to a cathode configuration having a perforated dielectric covering for stabilizing glow plasma discharges.

RELATED ART

A "plasma" is a partially ionized gas composed of ions, electrons, and neutral species. This state of matter is produced by high temperatures or strong electric fields created by constant or pulsed DC current, AC current or time varying (e.g., R.F. or microwave) electromagnetic fields. Discharge plasmas are produced when free electrons are energized by electric fields in a background of neutral atoms / molecules. These electrons cause electron - atom / molecule collisions which transfer energy to the atoms / molecules and form a variety of species which may include photons, metastables, atomic excited states, free radicals, molecular fragments, monomers, electrons, and ions. The neutral gas becomes partially (or fully) ionized and is able to conduct currents. The plasma species are chemically active and/or can physically modify the surface of materials and may therefore serve as the basis of new chemical compounds and may be used to modify existing compounds. Discharge plasmas can also produce useful amounts of optical radiation and can therefore be used in lighting. There are additionally many other uses for such plasmas. Glow discharges and arc discharges produce a class of plasmas known as current-maintained plasmas, since they are maintained by the passage of current therethrough. Such plasmas conduct only because current is passed therethrough and the conductivity falls off quickly if the source of energy to the charge carriers is removed.

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Transition points exist at which the various attributes of the discharge and discharge plasma change from the characteristics of a glow discharge to the characteristics of an arc discharge. The characteristics that distinguish arc from glow are a high gas temperature and a low cathode fall potential, though it is also possible to have a high gas temperature associated with a high cathode fall and vice versa.

The transition from glow to arc passes through a series of stable or quasi-stable states. However, the final step from abnormal glow to arc is very often an unstable change, since a very large potential drop in the series resistance would be required to make it stable. If there is no series resistance, the transition may take place very rapidly, without equilibrium being achieved in any intermediate stage. This transition becomes more rapid as the pressure of the background neutral gas increases towards atmospheric pressure.

In the past, there have been efforts to stabilize glow plasma discharges in various ways such as the use of source frequencies over 1 kHz, insertion of a dielectric plate (or plates) between two metal electrodes and by using helium dilution gas. Additionally, other attempts to stabilize the glow plasma discharge include placement of an insulated plate on the lower electrode, use of a brush-style upper electrode, and the use of a metal upper plate in combination with an insulating plate on the bottom thereof. However, there are certain drawbacks with these requirements in that, e.g. helium is expensive and there are physical limitations based on the structure of the electrodes and the insulated plates.

Past work in this area include a series of articles by Okazaki, Satiko, et al., starting back in 1989 with the article by Kanazaw, S., et al., entitled, "Glow Plasma Treatment at Atmospheric Pressure for Surface Modification and Film Deposition," Nuclear Instruments and Methods in Physics Research (1989) Elsevier Science Publishers, B.V. (North-Holland Physics Publishing Division), which disclosed a plasma treatment at atmospheric pressure to stabilize glow plasma by treatment in a gas which includes carbon-tetrafluoride (CF₄), using helium as the dilute gas and using an insulating plate on a lower electrode, and using a brush style electrode for the upper electrode to create a stable discharge at 3,000 Hz.

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Yokoyama, T., et al., "The improvement of the atmospheric-pressure glow plasma method and the deposition of organic films," Journal of Physics (1990) IOP Publishing, Ltd., discloses an improved atmospheric pressure glow discharge plasma method for treating metallic substrates wherein the middle plate upper electrode is improved by use of an insulating plate set on its bottom.

Yokoyama, T. et al., "The mechanism of the stabilization of glow plasma at atmospheric pressure," Journal of Physics (1990) IOP Publishing, Ltd., discloses stabilization of a glow discharge of atmospheric pressure by controlling three conditions, namely, the use of a high frequency source, the use of helium gas for dilution, and the insertion of a dielectric plate between electrodes.

Okazaki, Satiko, et al., "Appearance of stable glow discharge in air, argon, oxygen, and nitrogen at atmospheric pressure using a 50 Hz source," Journal of Physics, (1993) IOP Publishing, Ltd., discloses a method and apparatus for stabilizing glow discharge by making the discharge occur in the early stages of the Kekez curve, and at a lower discharge breakdown voltage, by use of a metal wire mesh electrode.

Kogoma, Masuhiro, et al., "Raising of ozone formation efficiency in a homogeneous glow discharge plasma at atmospheric pressure," Journal of Physics (1994) IOP Publishing, Ltd., discloses an ozone formation apparatus for increasing the efficiencies of ozone formation by use of a homogenous glow discharge at atmospheric pressure to create ozone efficiencies increased to about 10% in air to a maximum of 15% in oxygen over conventional filamentary current discharges in gas. The increase is attributed to better collision efficiency among electrons and molecules and to a lower increase in temperature than in discharge filaments of a silent electric discharge.

Other work in this area includes U.S. Patent No. 4, 498,551 to Hoag, entitled, "Discharge Electrode for a Gas Discharge Device," which uses pin-shaped electrodes which are effectively cooled in the glass flow and which promote a stable glow-discharge.

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U.S. Patent No. 5,387,842 dated February 7, 1995 to Roth, et al., entitled, "Steady-State, Glow Discharge Plasma," and U.S. Patent No. 5,414,324 dated May 9, 1995 to Roth, et al., entitled "One Atmosphere, Uniform Glow Discharge Plasma," both disclose a steady state glow discharge plasma generated between a pair of insulated metal plate electrodes spaced up to five centimeters apart and energized with a RMS potential of 1 to 5 KV at 1 to 100 Khz. The space between the electrodes is occupied by a noble gas such as helium, neon, argon, etc., and it may also include air. The radio frequency amplifier means for generating and maintaining a glow discharge plasma includes an impedance matching network. The arc of electric field is high enough to trap the positive ions of the plasma between the electrodes, but not so high that the electrons of the plasma are also trapped during a half cycle of the RF voltage.

None of these previous efforts disclose all of the benefits of the present invention, nor does the prior art teach or suggest all of the elements of the present invention.

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OBJECTS AND SUMMARY OF THE INVENTION

It is a primary object of the present invention to provide a method and apparatus for stabilizing glow discharge plasmas.

5 It is another object of the present invention to provide a method and apparatus for suppressing the glow-to-arc transition in glow discharges.

It is an additional object of the present invention to provide a method and apparatus to stabilize glow discharge plasmas in a constant electric field.

10 It is even an additional object of the present invention to provide a method and apparatus to stabilize glow discharge plasmas in time varying electric fields.

15 It is another object of the invention to provide a cathode configuration for stabilizing the cathode fall in a glow discharge.

It is an additional object of the present invention to provide a method and apparatus for suppressing the glow-to-arc transition for a wide range of operating conditions and a wide range of operating pressures.

20 It is another object of the present invention to provide a metal cathode covered with a perforated dielectric for suppressing the glow-to-arc transition and stabilizing glow discharge.

25 It is also an object of the present invention to provide a method and apparatus for suppressing the glow-to-arc transition for a wide range of electric field strengths.

It is an additional object of the present invention to tailor the characteristics of fuel combustion by field augmentation with suppression of the glow-to-arc transition.

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It is an additional object of the present invention to tailor the characteristics of plasma assisted materials processing by suppressing the glow-to-arc transition in material processing.

It is another object of the present invention to suppress the glow-to-arc transition and to allow for large volume plasma work at atmospheric pressure.

It is an additional object of the present invention to reduce the complexity and costs of plasma processing of materials.

It is even a further object of the present invention to improve pollution control through the use of plasmas at high pressures by suppressing the glow-to-arc transition.

These and other objects are achieved by the method and apparatus of the present invention for stabilizing glow plasma discharges by suppressing the transition from glow-to-arc. A dielectric plate having an upper surface and a lower surface and a plurality of holes extending therethrough is positioned over the cathode and held in place thereon by a collar. Each of the holes acts as a separate active current limiting micro-channel that prevents the overall current density from increasing above the threshold for the glow-to-arc transition.



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BRIEF DESCRIPTION OF THE DRAWINGS

Other important objects and features of the invention will be apparent from the following Detailed Description of the Invention when read in context with the accompanying drawings in which:

FIG. 1 is an exploded perspective view of the perforated dielectric covering a cathode of a DC embodiment of the present invention.

FIG. 2 is a schematic view of a circuit configuration for use with the present invention.

FIG. 3 is a graph of voltage v. current for applied voltage, glow voltage, and arc voltage in Argon at 40 Torr.

FIG. 4 is a graph of voltage v. current for applied voltage, glow voltage, and arc voltage in Argon at 20 Torr.

FIGS. 5a and 5b are graphs of applied voltage, glow voltage and arc voltage with and without the perforated dielectric of the present invention.

FIG. 6a is a photograph showing an arc discharge and **FIG 6b** is a photograph showing a glow discharge.

FIG. 7 is a side plan view of another embodiment of the present invention for an RF field wherein perforated dielectrics are positioned over both electrodes.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is directed to a method and apparatus for stabilizing plasma glow discharges by suppressing the glow-to-arc transition in DC, RF electric field, pulsed DC, AC current or any other glow discharges which evolves from the cathode fall region. Referring to FIG. 1, it can be seen that a new cathode configuration has been developed to stabilize the cathode fall and suppress the glow-to-arc transition for a wide range of operating conditions. Accordingly, a stable glow discharge can be maintained with the cathode configuration of the present invention for a very wide range of operating pressures (up to atmospheric pressures) and in a wide range of electric field strengths.

Referring to FIG. 1, which shows a DC embodiment, the cathode of the present invention, generally indicated at 10, comprises a metal cathode 20 (aluminum, stainless steel, etc.), covered with a perforated dielectric 30 positioned to face an upper electrode 40. The perforated dielectric 30 may be retained on the cathode 20 by a collar 35 that fits over cathode 20 and has an aperture 36 therethrough, or may be formed as part of a cap or cover for the cathode 20, or may be positioned thereon and held in place thereon in any other manner known in the art.

Importantly, the perforated dielectric can be formed of any desired dielectric type substance such as quartz, silicon nitride, silicon carbide, etc., even glass. The dielectric is preferably formed of a material that can withstand high temperatures. Essentially, a perforated dielectric comprises a sieve of holes of micron dimensions. The center to center distance of the holes is of the same level of dimension. Hole dimensions are critical for particular applications. In trials discussed hereinafter, a dielectric having 10 micron holes with a center to center distance between the holes of 12 microns was used. Hole dimensions can vary from 5 to 200 μm for the hole diameter and from between 100 μm to 2 mm for the hole length (thickness of the dielectric). Importantly, the ratio of the hole diameter to the dielectric thickness is an important factor and something that can be controlled depending upon the application. One example of such a ratio could be 10 to 1, the hole diameter being one-tenth of the thickness of the dielectric.

The perforated dielectric can be made by laser ablation. Blanks for dielectric plates made by Norton International can be used, and function in a desirable matter (a dielectric having a hole diameter of 10 μm , and a hole length of 0.6 mm). The hole diameter, hole lengths, hole density, and material can be varied to optimize the invention for a particular application. Any silicon carbide wafer can be perforated by laser ablation to form a perforated dielectric for use in connection with the present invention.

Referring to FIG. 2, shows a circuit that has been used to conduct trials of the present invention that will hereinafter be discussed, which can be used with the cathode configuration of the present invention to effect a stable DC glow plasma discharge. The circuit is governed by equation (1):

$$V_s = I_1 (R_1 + R_2) = \frac{1}{R_1} (R_1 + R_2) V \quad \text{Equation (1)}$$

where $I_2 = 4I_1$

$$R_E = \frac{R_3}{4} \quad (\text{for } R_1 \ll R_3)$$

$$V_g = V_s - I_g R_3$$

$$V_d = V_s - I_d R_3$$

In this way, by measuring voltage V across resistor R , and current i through resistor R_1 , we can calculate the voltage and the current across the cathode.

The present invention allows DC glow discharges, which have a well known instability that limits the operating range, to operate at much higher pressure up to atmospheric pressures. Accordingly, this stabilization allows for applications in many aspects of material processing, pollution remediation, novel lighting devices, and discharge-enhanced combustion.

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The perforated dielectric covering the metal cathode stabilizes the cathode fall region of the DC discharge by breaking the discharge up into a large number of separate micro-channels. Each of the holes comprising the perforated dielectric acts as a separate, active current-limiting micro-channel. Particle losses due to wall effects and the finite volume of each channel place an upper limit on the electrical conductivity of each channel, and therefore place an upper limit on the current density that it can carry. This prevents the current density from increasing above the threshold for the glow-to-arc transition.

Additionally, it should be noted that a dielectric material could be directly deposited in a proper geometry directly onto a cathode by a vapor deposition or other process to apply the dielectric directly to the cathode. In this way, the cathode itself becomes an active current-limiting device.

A prototype DC glow discharge apparatus was set up using a parallel plate electrode arrangement in an Argon atmosphere of between 10-100 Torr, to illustrate the present invention.

At these pressures, the phases of the glow-to-arc transition can be readily shown because the transition is sufficiently slow. The transition at atmospheric pressures occurs very rapidly and is difficult to observe. However, it should be pointed out that the present invention is designed to be used at pressures up to atmospheric pressures. Current voltage characteristics were recorded for a variety of operating conditions using a standard metal (Al) cathode. The measured curves show the well-known first transition corresponding to the breakdown of gas in the formation of a stable glow discharge, followed by a prominent second transition characteristic of the transition from the glow regime to an arc which creates a filamentary (high current density) channel. Subsequently, the conventional cathode was replaced by the new cathode design and the same current-voltage curves were recorded. All curves showed only the first transition to the stable high-current glow. No indications of the previously observed glow-to-arc transition were found under any operating conditions. The spatial distribution of the discharge is also diffuse.

Referring now to **FIG. 3**, a graph of voltage vs. current for applied voltage (V_G), glow voltage (V_g) and arc voltage (V_d) is shown for Argon at 40 Torr. **FIG. 4** shows a graph of voltage

vs. current for applied voltage (VG), glow voltage (Vg), and arc voltage (Vd) in Argon at 20 Torr.

FIGS. 5a and 5b are graphs of the applied voltage and glow-to-arc voltage with and without the perforated dielectric of the present invention. These figures show the stabilization of the glow plasma discharge. In a first Stage A, there is no current. In the second Stage B, voltage is applied, but current stays at zero. In a third Stage C, a glow discharge is achieved. As seen in **FIG. 5a**, the glow quickly goes to arc D, while in **FIG. 5b**, the perforated dielectric suppresses the glow-to-arc transition and stabilizes the glow discharge such that there is no arc.

FIG. 6a is a photograph showing an arc discharge which creates a filamentary (high current density) channel. **FIG. 6b** is a photograph showing a glow discharge characterized by a uniform glow discharge.

FIG. 7 is a side plan view of an RF discharge embodiment of the present invention wherein the perforated dielectric is positioned over both electrodes. As can be seen electrodes **120** and **140** are both covered by a perforated dielectric **130**. Because the current reverses itself in a RF electric field, the dielectric **130** must be positioned over both electrodes **120** and **140**, as both electrodes alternately serve as cathodes. By this configuration, the glow discharge can be sustained under broader operating conditions. Such a configuration results in a frequency independent and size independent device.

By applying the method and apparatus of the present invention to large volume plasmas at atmospheric pressures, it is possible to increase the energy released during combustion of fuels to levels several times higher than the Heating Value of the fuel. Efforts in this area in the past have failed because the distribution of energy is required over a substantial volume and cannot be concentrated in a small area. Because of the glow-to-arc transition, there has been tendency to produce arcs of a very high energy level with the rest of the volume remaining at a normal combustion level. By suppressing the glow-to-arc transition and stabilizing the plasma glow, the method and apparatus of the present invention overcomes the limitations of the prior attempts and results in an enhancement of the combustion process resulting in much higher energy densities than

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could be previously achieved.

Additional applications of the present invention may occur in the field of air pollution remediation where stabilization of the glow-to-arc transition may result in real time destruction of constituents of air emissions from manufacturing operations in remediation of soil and ground water pollution, in large volumes at high pressures. By suppressing the glow-to-arc transition and stabilizing the glow discharge, the present invention creates large volume plasmas to destroy the polluting vapors at higher efficiencies with reduced cost. There could be additional applications relating to the destruction of combustion by-products such as NO_x and SO_x which have heretofore been destroyed by pulsed corona and barrier discharges.

The present invention is additionally applicable to the cleaning of lithography sheet surfaces in atmospheric pressures. Additionally, there may be possible utility for large area surface cleaning at atmospheric pressure for curing polymer films. By being able to operate at atmospheric pressure, a great advantage is achieved over the high processing cost required in a vacuum process. Additionally, the present invention can be used for pretreatment of semi-conductors, glasses, and polymers which are to be used for direct metal ion beam processing.

Additionally, an atmospheric pressure glow discharge plasma can be used to sterilize biologically contaminated surfaces. Current techniques in this area utilize high temperatures, strong chemicals, and/or ultraviolet radiation to sterilize contaminated items. However, there are problems with these approaches in that the processes are time intensive and potentially hazardous and result in the formation of potentially hazardous by-products. It has been demonstrated that materials exposed to a one-atmosphere pressure glow discharge plasma can be sterilized of biological contaminants in under one minute.

Having thus described the invention in detail, it is to be understood that the foregoing description is not intended to limit the spirit and scope thereof. What is desired to be protected by the Letters Patent is set forth in the appended claims.

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CLAIMSWhat is claimed is:

1. An apparatus for generating and maintaining a glow plasma discharge comprising:

a pair of electrodes positioned in facing relation;

a perforated dielectric placed over one of the electrodes; and

an electric field generated between the electrodes.

2. The apparatus of claim 1 wherein the perforated dielectric comprises a plurality of apertures, each aperture having a diameter ranging from 5 to 200 μ m.

3. The apparatus of claim 2 wherein the dielectric is between 100 μ m and 2mm in thickness.

4. The apparatus of claim 3 wherein the dielectric comprises silicon nitride.

5. The apparatus of claim 3 wherein the dielectric comprises silicon carbide.

6. The apparatus of claim 3 wherein a second dielectric is placed over the other of the electrodes.

7. The apparatus of claim 3 wherein the dielectric is a high temperature dielectric able to withstand high temperatures.

8. A cathode for generating and maintaining a glow plasma discharge comprising:

an electrode;

perforated dielectric means placed over the electrode; and

means for retaining the perforated dielectric on the electrode.

9. The apparatus of claim 8 wherein the perforated dielectric means comprises a plurality of apertures, each aperture having a diameter ranging from 5 to 200 μ m.

10. The apparatus of claim 9 wherein the perforated dielectric means is between 100 μ m and 2mm in thickness.

11. The apparatus of claim 10 wherein the perforated dielectric means comprises silicon nitride.

12. The apparatus of claim 10 wherein the perforated dielectric means comprises silicon carbide.

13. The apparatus of claim 11 wherein a second perforated dielectric means is placed over the other of the electrodes.

14. The apparatus of claim 11 wherein the perforated dielectric means is a high temperature dielectric able to withstand high temperatures.

15. A method of stabilizing glow-to-arc transition for a discharge plasma comprising the steps of:

positioning opposing electrodes in a facing relation;

providing a perforated dielectric having a plurality of apertures therethrough; and

covering one of the electrodes with a perforated dielectric.

16. The method of claim 15 further comprising the step of covering the other of the electrodes with a perforated dielectric so that both electrodes are covered.

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17. The method of claim 15 wherein the step of covering one of the electrodes comprises placing a dielectric material thereon and retaining the dielectric material thereon.

18. The method of claim 17 wherein the step of retaining the dielectric material on one of the electrodes further includes the step of placing a retaining collar over the dielectric.

19. The method of claim 15 wherein the step of covering one of the electrodes comprises the step of depositing a dielectric on one of the electrodes.

20. The method of claim 19 wherein the step of depositing a dielectric on one of the electrodes comprises vapor deposition.

21. An apparatus for generating and maintaining a glow plasma discharge comprising:

a pair of electrodes positioned in facing relation, with a space therebetween;

a perforated dielectric positioned between the electrodes and partially occupying the space;
and

an electric field generated between the electrodes.

AMENDED CLAIMS

[received by the International Bureau on 28 July 1998 (28.07.98);
original claims 1,4-15 and 21 amended; new claims 22-24 added;
remaining claims unchanged (3 pages)]

What is claimed is:

1. A glow plasma discharge apparatus for generating and maintaining a glow plasma discharge comprising:
 - a pair of electrodes positioned in facing relation having a space therebetween;
 - a perforated dielectric placed over one of the electrodes and partially occupying the space;
 - and
 - an electric field generated between the electrodes.
2. The apparatus of claim 1 wherein the perforated dielectric comprises a plurality of apertures, each aperture having a diameter ranging from 5 to 200 μ m.
3. The apparatus of claim 2 wherein the dielectric is between 100 μ m and 2mm in thickness.
4. The apparatus of claim 1 wherein the dielectric comprises silicon nitride.
5. The apparatus of claim 1 wherein the dielectric comprises silicon carbide.
6. The apparatus of claim 1 wherein a second dielectric is placed over the other of the electrodes.
7. The apparatus of claim 1 wherein the dielectric is a high temperature dielectric able to withstand high temperatures.
8. A cathode in a glow plasma discharge apparatus for generating and maintaining a glow plasma discharge comprising:
 - an electrode;
 - current limiting means placed over the electrode for limiting current density associated with the electrode; and
 - means for retaining the current limiting means on the electrode.

9. The apparatus of claim 8 wherein the current limiting means comprises a plurality of apertures, each aperture having a diameter ranging from 5 to 200 μ m.
10. The apparatus of claim 9 wherein the current limiting means is between 100 μ m and 2mm in thickness.
11. The apparatus of claim 8 wherein the current limiting means comprises silicon nitride.
12. The apparatus of claim 8 wherein the current limiting means comprises silicon carbide.
13. The apparatus of claim 8 wherein a second current limiting means is placed over the other of the electrodes.
14. The apparatus of claim 8 wherein the current limiting means is a high temperature dielectric able to withstand high temperatures.
15. A method of stabilizing glow-to-arc transition for a discharge plasma comprising the steps of:
 - positioning opposing electrodes in a facing relation with a space therebetween;
 - providing a perforated dielectric having a plurality of apertures therethrough;
 - covering one of the electrodes with the perforated dielectric by positioning the perforated dielectric to partially occupy the space between the opposing electrodes; and
 - generating an electric field between the electrodes.
16. The method of claim 15 further comprising the step of covering the other of the electrodes with a perforated dielectric so that both electrodes are covered.
17. The method of claim 15 wherein the step of covering one of the electrodes comprises placing a dielectric material thereon and retaining the dielectric material thereon.

18. The method of claim 17 wherein the step of retaining the dielectric material on one of the electrodes further includes the step of placing a retaining collar over the dielectric.

19. The method of claim 15 wherein the step of covering one of the electrodes comprises the step of depositing a dielectric on one of the electrodes.

20. The method of claim 19 wherein the step of depositing a dielectric on one of the electrodes comprises vapor deposition.

21. A glow plasma discharge apparatus for generating and maintaining a glow plasma discharge comprising:

- a pair of electrodes positioned in facing relation;
- an electric field generated between the electrodes; and
- a dielectric having a plurality of apertures positioned between the electrodes, the apertures sized to limit current density between the electrodes from increasing above a pre-determined threshold.

22. The apparatus of claim 21 further comprising collar means for retaining the dielectric on one of the electrodes.

23. The apparatus of claim 21 wherein the dielectric is formed integrally with one of the electrodes.

24. The apparatus of claim 21 wherein the plurality of apertures comprises a sieve of holes of micron dimensions.

FIG. 1

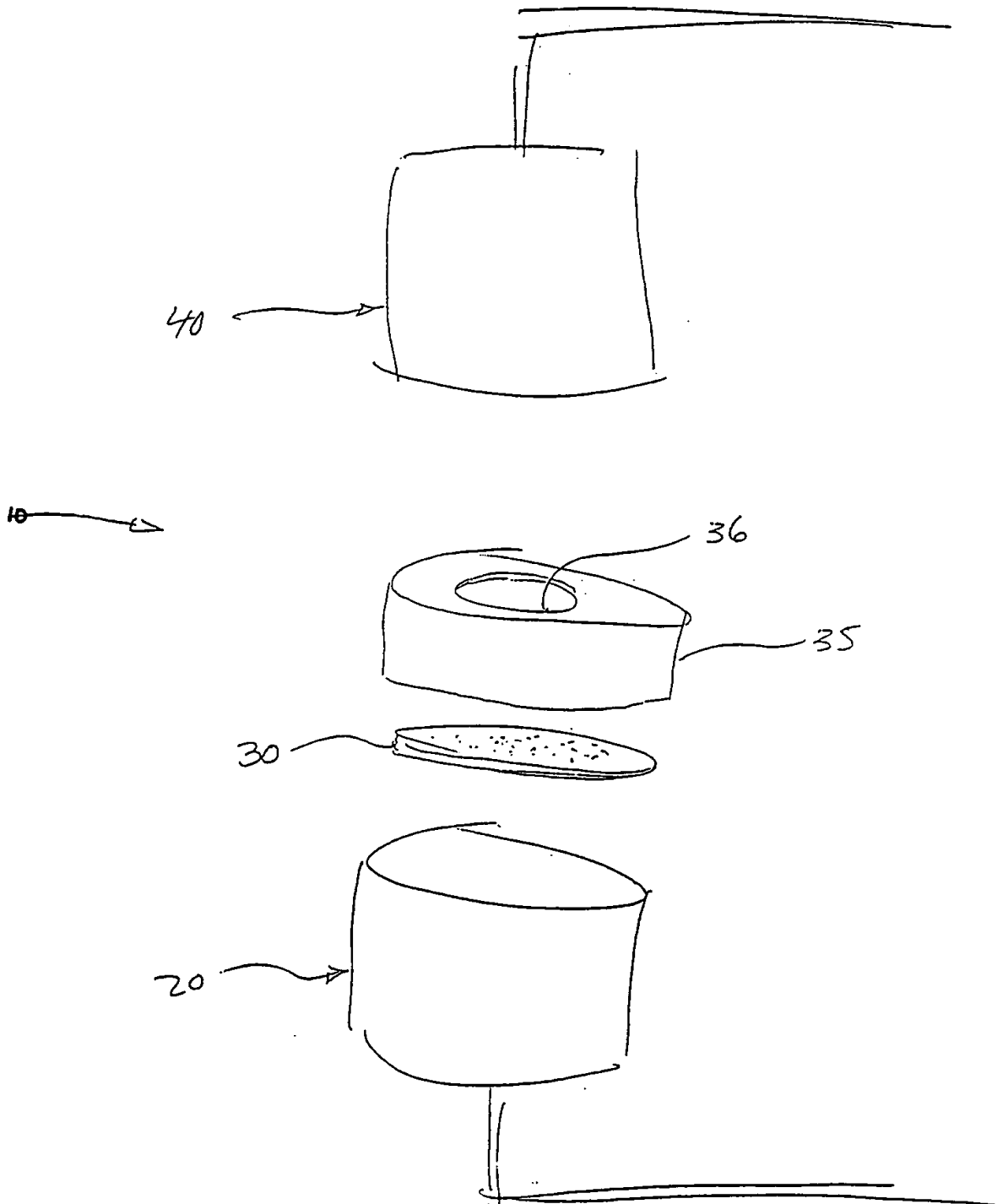


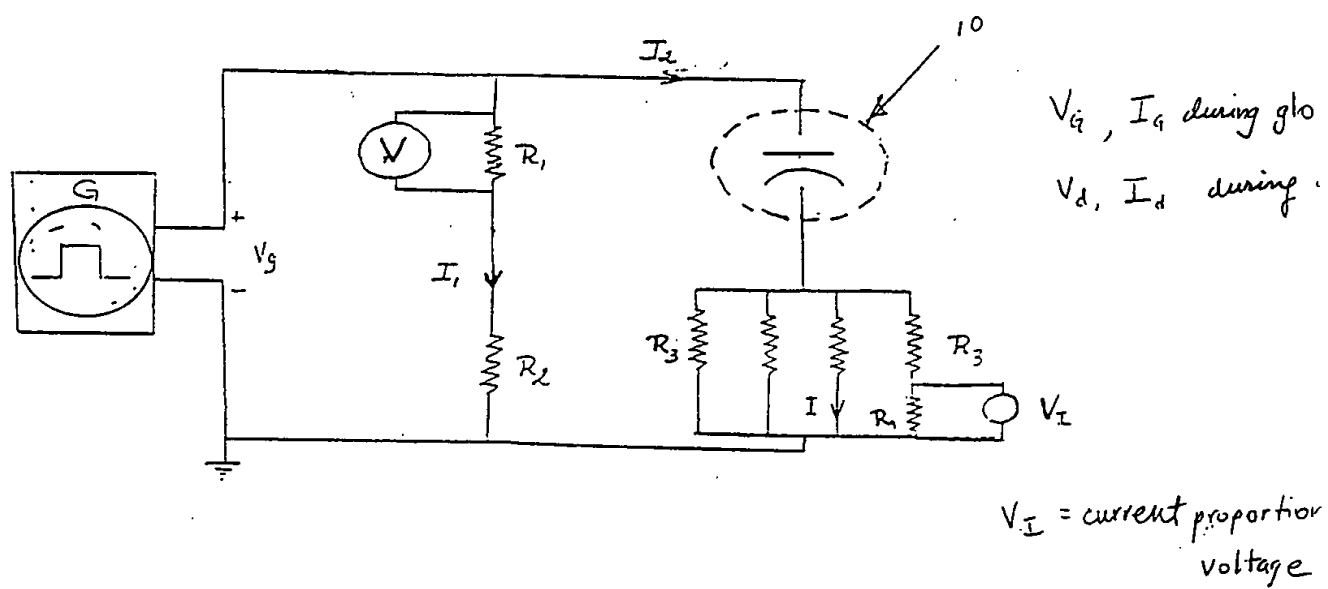
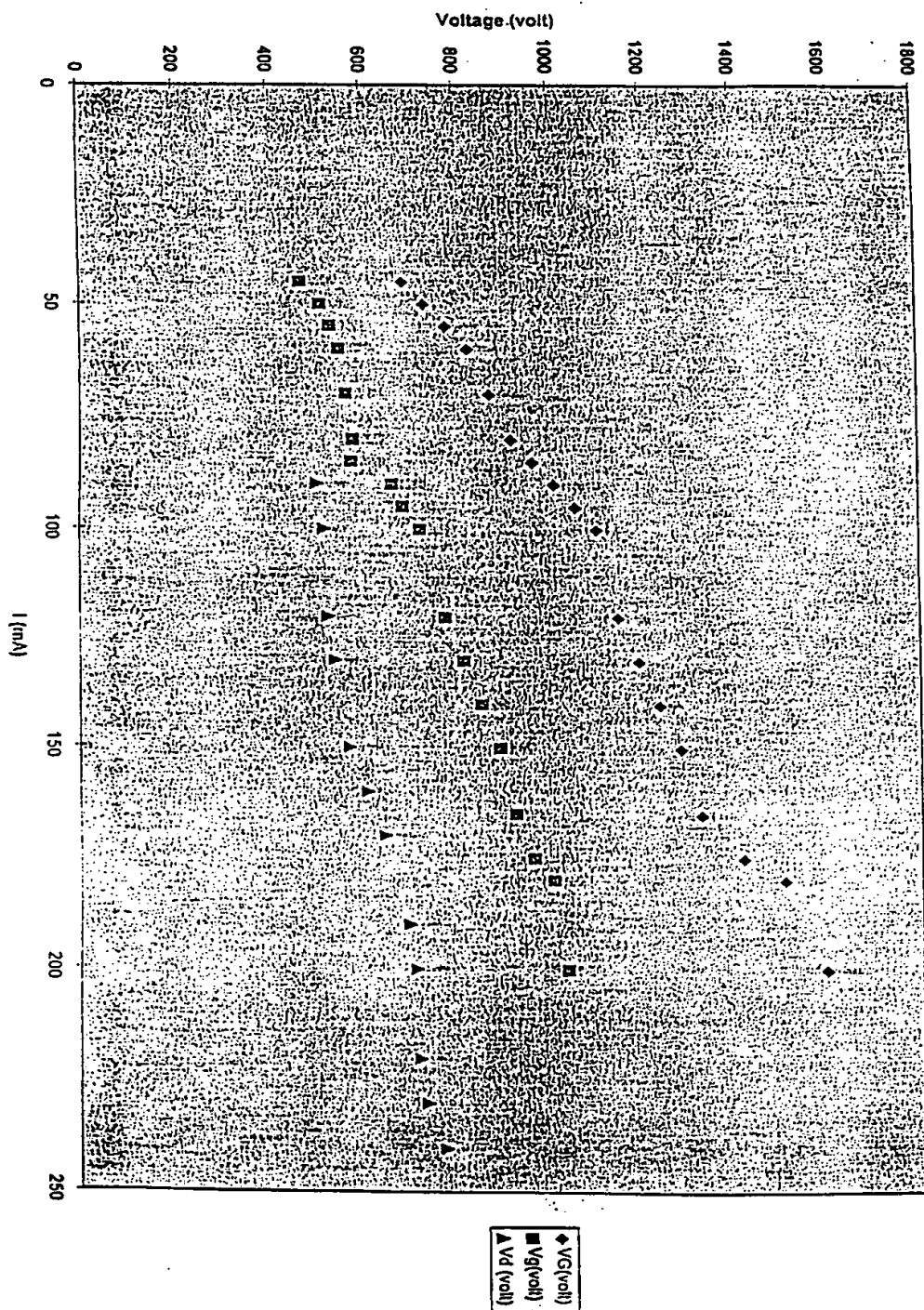
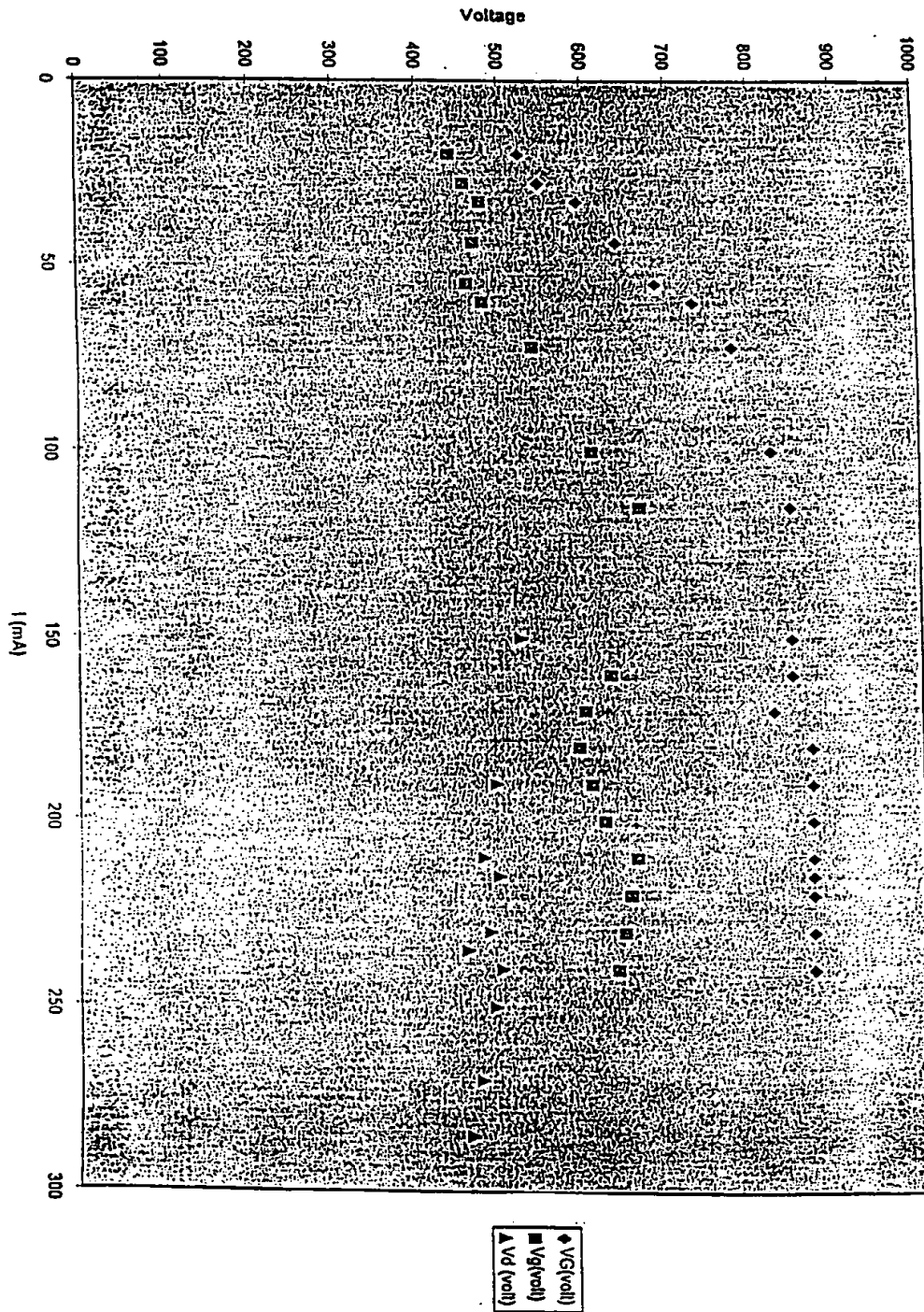
FIG. 2

Fig. 3

Discharge in Ar (40 Torr)





Discharge in Ar (20 Torr)

Fig. 4

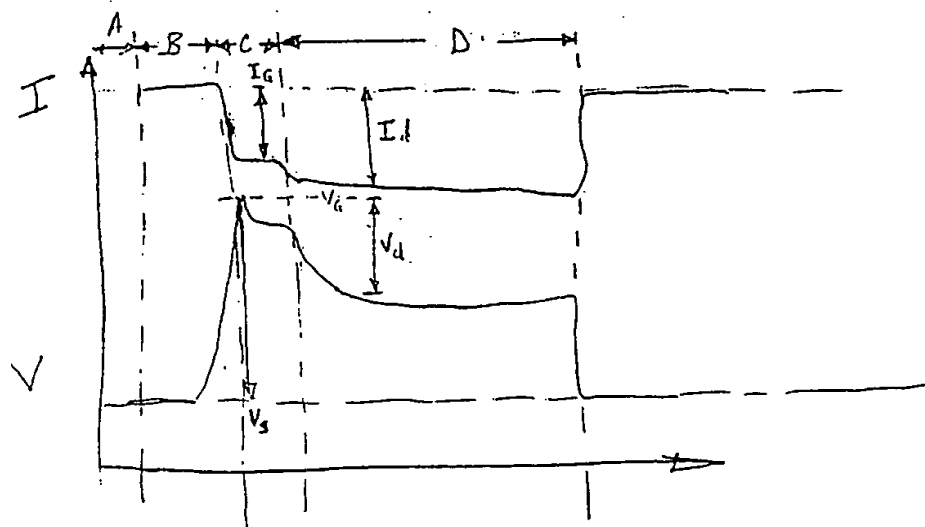
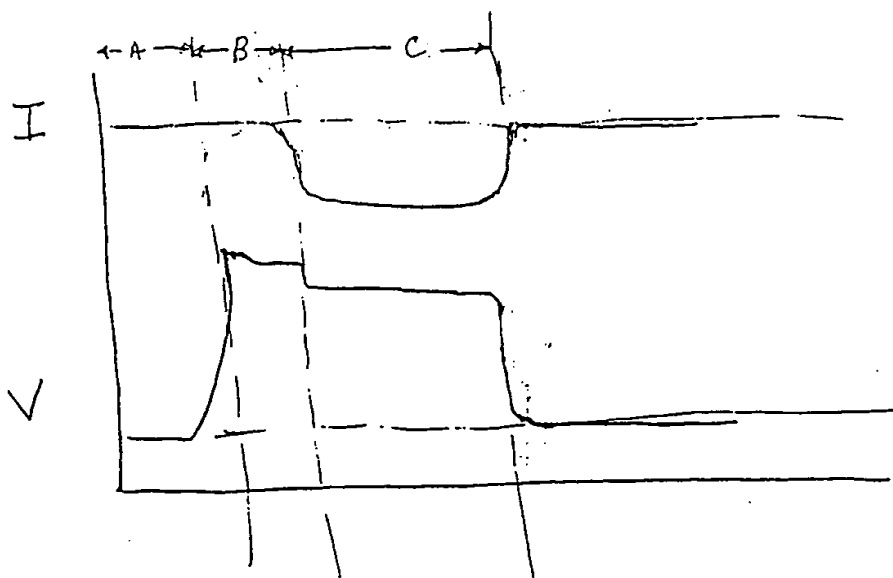
FIG. 5aFIG 5b

FIG. 6a



Fig. 6b

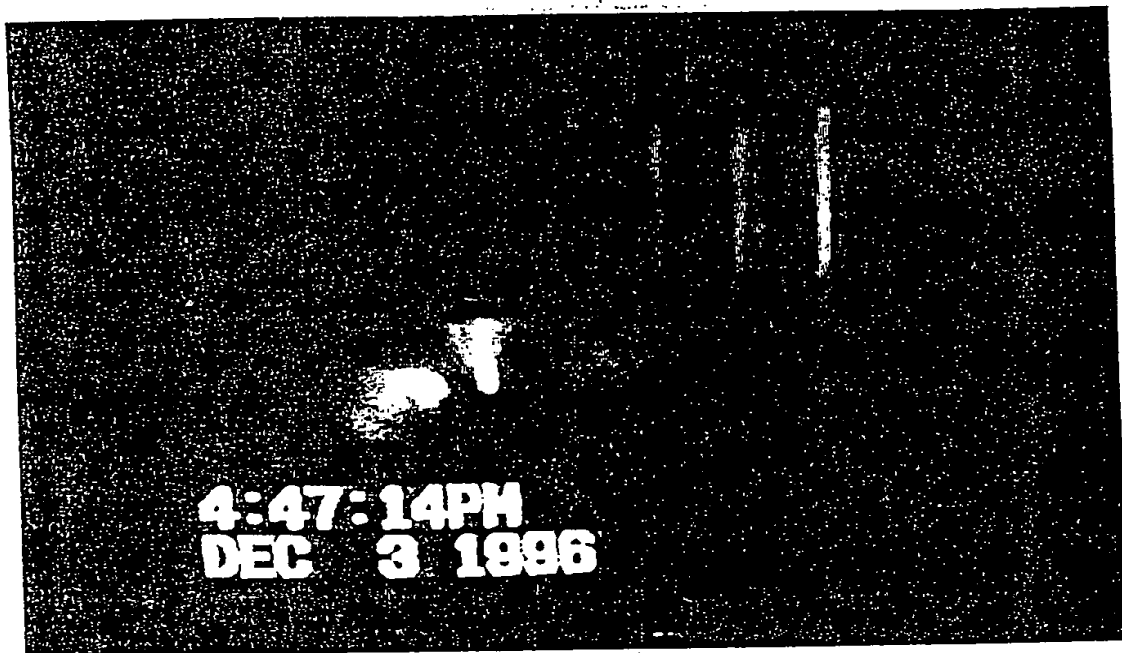
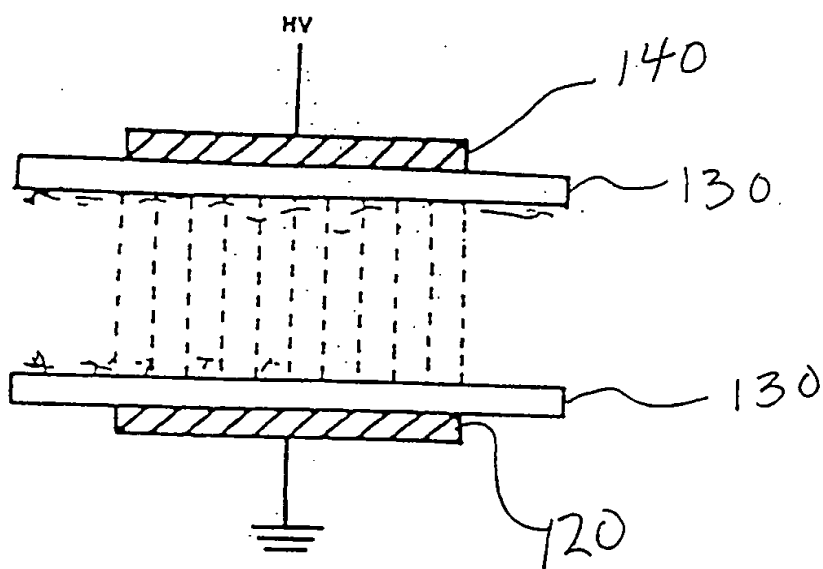


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/05174

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H01J 17/49

US CL :313/231.31, 582, 583,

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 313/231.31, 582, 583, 586, 619; 315/111.21, 111.71

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NoneElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)
None

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3,914,642 A (Coderre et al) 21 October 1975 (21-10-75), lines 30-45 of column 2.	1, 8, 21

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	*T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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Date of the actual completion of the international search

07 MAY 1998

Date of mailing of the international search report

15 JUN 1998

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